Cross Sections for Electron Scattering by Ground State Ba; Elastic Scattering and Excitation of the . . .6s6p $^1P_1$ Level

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Abstract

Differential cross sections for elastic and inelastic (6s6p $^1P_1$) electron scattering from ground state Ba atom have been measured at 5eV, 10eV, 15eV, and 20eV impact energies in the angular range from 0^0 to 130^0. Extrapolation to the larger angles have been performed using theoretical calculations as a guide, and integral and momentum transfer cross sections were derived. Theoretical calculations based on two channel close coupling and relativistic and non-relativistic distorted wave methods have been compared with the present results. Good agreement between experiment and various theoretical results is found at small scattering angles but significant deviations exist at larger scattering angles.

1. Introduction

Electron collision processes involving, Ba atoms, both in their ground state and excited state.s, are of interest both from theoretical and from practical view points. Ba is an alkaline earth atom which consists of two valence electrons outside of a relatively inert core. This element inhibits a large variety of characteristic behaviors of complex atoms while, from the. experimental point of view, it is relatively easy to work with. Ba has been utilized for diagnostic purposes in ionospheric plasma release experiments (Wescott et al, 1980; Simons et al, 1981), and for controlling the. Conductivity of high current switches (Young and Rodriguez, 1997). However, measurement of absolute electron scattering cross sections of Ba atom is very limited because of the difficulty to normalize the. relative data to the absolute scale. The optical recitation function for the ($6s^2\ ^1S_0 \rightarrow 6s6p\ ^1P_1$) transition was measured by Aleksakhin et al (1975) and Chen and Gallagher (1976) in the impact energy (E_0) range from threshold to 300eV and to 1500eV V, respectively. Differential cross sections (DCS) for elastic scattering and for excitation of the. low lying levels were reported at E_0 = 5eV by Trajmar and Williams (19"/6), at 30eV by Trajmar (1977) and at 20, 30, 40, 60, 80 and 100eV by Jensen et al (1978). CI10ss section measurements for electron scattering by last.r-mcitexi Ba ($6s6p\ ^1P_1$) and cascade populated Ba ($6s5d\ ^{1,3}D$) species were carried out by Register et al (19"/8) at 30 and 100tV impact energies. Electron impact coherence parameters (EICP) for the ($6s^2\ ^1S_0 \rightarrow 6s6p\ ^1P_1$) excitation were determined by Zetner et al (1992 and 1993) and Li and Zetner (1993) at impact energies ranging from 20 to 80 eV. In the theoretical area, Gregory and Fink (1974) calculated elastic. DCS in the 100 to 1500CV" impact energy range using a relativistic scattering potential and solving the Dirac equation numerically. DCS for elastic scattering and for near threshold excitation to the $6s6p\ ^1P_1$ level were calculated by Fabrikant (1974, 1975 and 19-/9) using a two-state, Clew-ccmpling approximation. Later, Fabrikant (1980) reported DCS for elastic scattering and for the ($6s^2\ ^1S_0 \rightarrow 6s6p\ ^1P_1$) excitation at 20 and 30eV impact energies as well as integral elastic scatter ing cross sections in the ener gy range from 6 to 35eV using the same method. More recently, Clark et al (1989) obtained DCS for excitation to the 6s6p $^1P_1$ level in the S to 100eV i mpact energy range based on distorted wave approximat ion (DWA) and first order many body theory (FOMBT) calculations. They accounted for spin-orbit coupling in the atom, but neglected relativistic effects for the continuum electrons. With a similar approach, Clark et al (1992) also obtained DCS for electron impact excitation and deexcitation from the. Ba (6s6p $^1P_1$) level at 30eV impact energy. Srivastava et al (1992a) utilized a completel y relativistic distorted wave method (CRDW) to obtain 11(:S and EICP for the (6s^2 $^1S_0$ → 6s6p $^1P_1$) excitation pr ocess in the ?0 to 100cV impact ener gy range. Sr ivastava et al (1992b) al so r epor ted similar r esults for the (6s^2 $^1S_0$ → 6s5(1 $^1D_2$ and $^3D_{1,2,3}$) excitation processes.

The aim of the. present work was to extend the DCS measurements to impact energies below 20eV for elastic scattering and for excitation to the 6s6p $^1P_1$ level and to obtain the corresponding momentum transfer and integral cross sections. These cross sections will serve to normalize DCS's for other excitation and deexcitation processes and will allow the deduction of magnetic sublevel DCS's from EICP measurements. Compar isons with the.ordiml results ar e made to assess the reliability of the. calculational methods.

II. Experimental

The electron - impact spectrometer, used for the present measurements, is basicall y the. same. as the. one used and described by Jensen et al (1978), and Trajmar and Register (19S4), with some improvements. Double hemispherical energy selectors and cylindrical, electrostatic optics were used both in the electron gun anti detector. Typical beam curr ent was a few nano amper es, and the over all energy resol ut ion was about 80meV (FWHM). The Ba beam effused fmni a crucible., which was heated by a two-wire shielded, resistance heater at about 800 ^{0}C, and was further collimated to fro-m a target beam with a diameter of about 2mm (with a divergence of ± 5°) in the interaction region. The Ba beam could be chopped by a small flap which was electronically controlled and synchronized with the multichannel scaler. The scattered electrons were detected with a channel electron multiplier and energy-loss spectra were obtained by pulse counting and multichannel scaling techniques. The contact potential for the apparatus was determined by measuring the impact energy corresponding to the. well established He resonance in the elastic scattering channel at $\theta = 90^0$ and taking the true value. for this resonance as 19.37 eV. The true zero scattering angle was established on the basis Of symmetry in the inelastic scattering signal.

The measurement and normalization procedure consisted of several steps. In the first step, the scattering intensity associated with the excitation Of the.6s6p $^1P_1$ level was measured as a function of the scattering angle (θ) at fixed impact energies. In order to convert these. intensities to relative DCS, an effective volume correction factor, Obtained from the modeling calculations of Brinkmann and Trajmar (1981), was used. We have selected their curve C in Figure 1 which corresponds very closely to the scattering geometry, DCS behaviors and gas kinetic cross sections of the present measurements. In the second step, relative integral cross sections were obtained by extrapolating the DCS's to 180^0 scattering, angle and integrating them. These cress sections were then normalized to the. absolute scale by utilizing the optical excitation functions of Chen and Gallagher (1976). In order to correct approximately for the cascade. contributions in their optical measurements, we estimated the cascade contributions from the upper levels to the 6s6p $^1P_1$ level as 5 % at 5eV impact energy, 10% at 10 and 15eV, and 20% at 20eV impact energy. The absolute DCS's for the excitation of the 6s6p $^1P_1$ level were then obtained at various impact energies by using established absolute. integral cross sections. As a third step, the scattering intensity ratios for the 6s6p $^1P_1$ excitation and elastic scattering were determined. Since, at small scattering angles, there are significant background contributions to the elastic (and some minor contributions to the. inelastic) scattering signals, we had to chop the Ba beam. From the energy-loss spectra obtained With tile Ba beam on, we subtracted the corresponding energy-loss spectra with the Ba beam Off. The Ba beam on and off spectra were. scanned alternati vely with a 30 second intro val to establish the same experimental conditions in both cases. From the true elastic to inelastic scattering intensity ratios, obtained this way, we ded uced the absolute elast ic DCS's by utilizing the. absolute inelastic DCS's established in the second step. An assumption was made that the e ffective volume correction factors for the elastic and inelastic channels were. identical. The momentum transfer cross sections for elastic scattering were obtained from the integral of the absolute DCS's at 15 and 20eV impact energies using the [1-cm(d)] weighting factor.

The major source of error in the DCS's came from the. uncertainty of normalization standard, i.e.., the optical cross sections measured by Chen and Gallagher (1976). Although these authors claimed a 5% error in their results, additional error (about 15%) comes from the. estimation of cascade. contributions. other error contributions are estimated as: DCS extrapolations to zero and 180^0, about 10%; electron beam fluctuation, 3%; Ba beam fluctuation, 3%; and statistical errors, <3% at angles below 70^0, and <8% above 70^0. The total error in the present 1)C3'sise.stinlated to be about 25%.

111. Results and discussions

Measurements were. carried out at 5, 10, 15 and 20eV impact energies at O to 130^0 scattering angles for excitation to the Ba 6s6p $^1P_1$ level, and at 15 and 20eV impact energies and 10^0 to 130^0 angles for elastic scattering.. The DCS results are given in Table 1. The present results arc compared with the theoretical calculations and previous experimental data when available.. Figures 1-6 show the presently measured DCS curves and their comparisons with other measurements and calculations.

Figure 1 shows the absolute DCS's for Ba 6s6p $^1P_1$ excitation at 20eV impact energy. The present results are in excellent agreement with previous measurements of Jensen et al (1978) upto 130^0. The present data above 130^0 were obtained by extrapolation using the theoretical DWA results of Clark et al (1989) (their FDMT results are similar to DWA results, but only DWA results are used for comparison in this paper) as a guide. We note that theoretical calculations by different groups (Fabrikant (1980), Clark et al (1989) and Srivastava et al (1992)) show the same angular behavior at scattering angles above 130^0. Therefore, we consider the extrapolation to be very reasonable. Since there were no theoretical calculations available when Jensen et al (1978) did their measurement, their extrapolation above 130^0 went downward instead of going up as predicted by theoretical calculations. This caused, however, only negligible errors in their normalization because of the small DCS values at large scattering angles. All theoretical DCS's show a similar angular behavior, and are in good agreement with presently measured values at angles below 130^0. However, there are large discrepancies in the absolute values at higher angles, and some of the theoretical results differ from the presently measured results by almost an order of magnitude at some scattering angles. The results of Clark et al (1989) are, however very close to our results at all angles.

Fig.2 gives the absolute DCS's for Ba 6s6p $^1P_1$ excitation at 15eV impact energy. Only one theoretical calculation (Clark et al, 1989) is available for comparison. The agreement between theory and experiment is good in the 0° to 20^0 angular range, but there are significant discrepancies at higher angles. The present measurement reveals almost the same angular behavior for both 15eV and 20eV DCS, and clearly shows three minima occurring at around 30^0, 90^0 and 130^0. However, the theory predicts three minima at about 25^0, 70^0 and 110^0 for 15eV DCS, and there are large differences in the magnitude of the DCS's at some angles. No experimental data are available for comparison.

The absolute. DCS's for Ba 6s6p $^1P_1$ excitation at 10eV are shown in Fig.3. Again, only the. calculations of Clark et al (1989) are available for comparison. No other measurement has yet been made. There is a weak , but clear indication of three minima occurring at the same. scattering angles as in the 15eV and 20eV cam. Theoretical calculations by Clark et al (1989) indicate only two minima at about 30^0 and 120^0. Since the. 10eV DCS's change very gradually and smoothly above 30°, the difference in the. angular behavior between theory and present experiment is rather small but differences in the magnitude of DCS's are as large as a factor of ten at large angles.

The 5eV DCS's for Ba 6s6p $^1P_1$ excitation are shown in Fig.4 together with the theoretical calculations by Clark et al (1989) and the experimental data of Trajmar and Williams (1976). The DCS's show significant forward peaking but rather isotropic behavior above. 40° scattering angles. Again at low angles the results from the two measurements and from theory are in good agreement but significant disagreements exist at scattering angles larger than 50°.

Summarizing the DCS measurements for Ba 6s6p $^1P_1$ excitation, we find that rich features with three minima occur at 20eV impact energy which gradually fade away when impact energy is decreased. At 15eV and 10eV, the. three DCS minima are weaker, but remain at the same angles which are different from the theoretical calculations. At 5eV, the DCS varies little above. 40° , the same. behavior as predicted by the theory. in terms of magnitude, the agreement between experimental and theoretical results is generally good but order of magnitude deviations occur at intermediate and higher angles.

Elastic electron scattering differential cross sections were measured at 20eV and 15eV impact energies and are shown in Fig.5 and Fig.6, respectively, For 20eV energy, our measurements agree quite well with the only available calculation (Fabrikant (1980) using two-state, close-coupling method). Our data above 130° were obtained by extrapolation using the theory as a guidance. The only other measurement (Jensen et al,

1978) differs very significantly from the present results both in angular behavior and in magnitude, Since we employed a Ba beam chopper to take account of the scattering, signals from background scattering, particularly the stray electrons from the gun, the present measurements represent an i mprovement over the previous measurement of Jensen et al (1978). The 15eV elastic DCS's are given in Fig.6. No other theoretical anti experimental data are available. to compare with. Generally the ang ular behavior shows the same pattern as in the 20eV case. Therefore, we extrapolated the data above 130^0 and Mow 10^0 by using the 20eV theoretical DCS as a guide.

V]. (conclusions

The present work represents an extension of differential and integral elastic scattering and ($6s^2\,{}^1S_0 \rightarrow 6s6p\,{}^1P_1$) recitation cross sections to impact energies below 20eV. (comparison of the inelastic experimental results with theoretical calculations based on DWA (and FOMT), two state CC and CRDW methods at 20eV impact energy show good agreement at scattering below about 300 At larger scattering angles, only DWA results are in good agreement with experiment. At lower impact energies only DWA (and FOMT) results are available. in each case the agreement with experiment is still good at the small scattering angles but at angles above 300 order of magnitude deviations occur. For elastic scattering, the only theoretical results are from the 2-state CC calculations of Fabrikant (1 980) which agree well with experiment up to 1000. Above this angle the shape. of the the.mctic.al and experimental DCS curves are still very similar, but in magnitude they differ by about a factor of 8. Further theoretical work is desirable. to i mprove the. situation at intermediate anti large scat tering angles.

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Figure Captions

Fig. 1: 20eV DCS of Ba 6s6p $^1P_1$ stale. excitation. solid circle: presently measured values; solid triangle: measured value.s by Jensen et al (1978); open circle: calculations of Srivastava et al (1992.); open triangle: DWA. calculations of Clark et al (1989); open square: calculations of Fabrikant (J 980).

Fig.2: 15eV DCS of Ba 6s6p $^1P_1$ state excitation . solid circle: presently measured values; open triangle.: DWA calculations of Clark et al (1989).

Fig.3: 10eV DCS of Ba 6s6p $^1P_1$ state excitation. solid circle: presently measured values; open triangle: DWA calculations of Clark et al (1989).

Fig. 4: 5eV DCS of Ba 6s6p $^1P_1$ state. excitation. solid circle: presently measured values; solid triangle.: measured values by Trajmar and Williams (1976); open triangle: DWA calculations of Clark et al (1989).

Fig.5: 20eV DCS of Ba elastic scattering. solid circle.: prc.sent results; solid triangle: measured values by Jensen et al (1978); open square.: calculations of Fabrikant (1980).

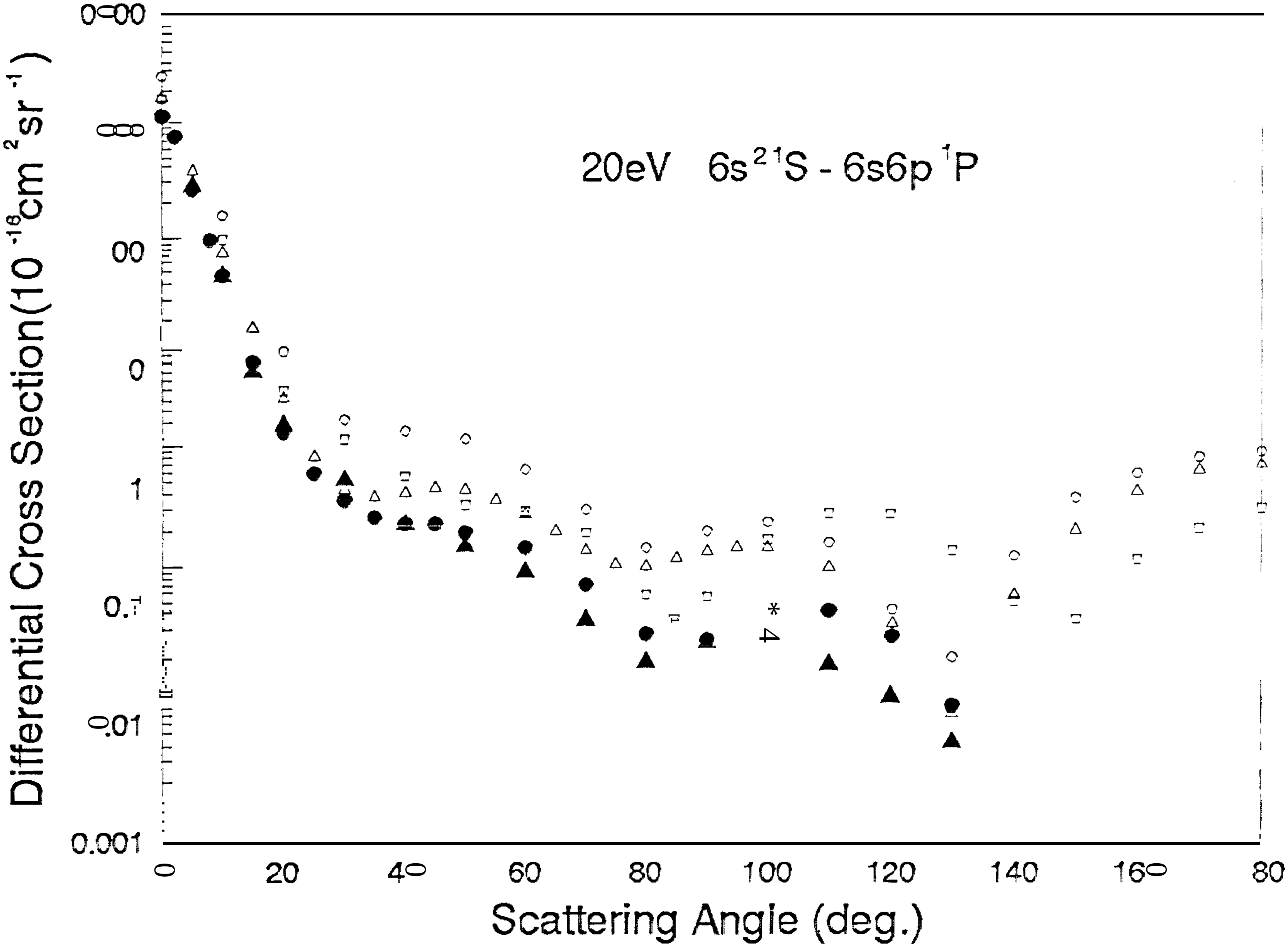
Fig.6: Present results of 15eV DCS of Ba elastic scattering..

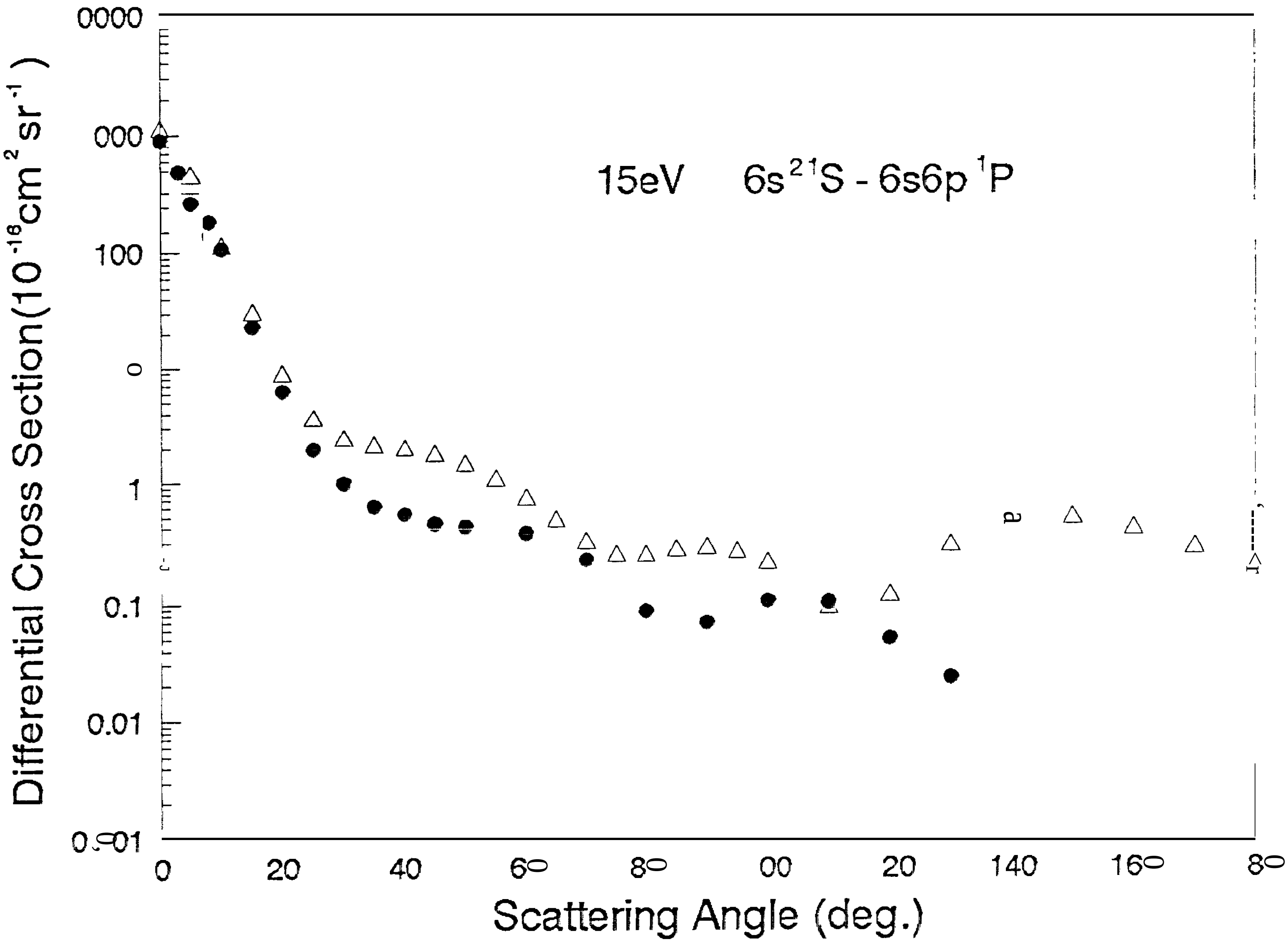
'J'able. 1: Differential cross sections Of electron scattering from Ba (in units Of 1()-] ^{6}cm^{2}sr^{-1})
(The values in the parentheses arc extrapolated by computer fitting)

θ(deg.)	E_0= 5eV	E_0=10eV	E_0= 15eV		E_0= 20eV	
	6p ^{1}P	6p ^{1}P	Elastic	6p ^{1}P	Elastic	6p ^{1}P
0	164	409	(300)	904	(337)	1105
2	(123)	286	(287)	(604)	(267)	549
5	91.9	200	(2 36)	324	(177)	331
8	(79.8)	135	(164)	183	(106)	124
10	72.1	114	114	108	69.6	62.2
15	38.9	49.9	20.7	23.4	15.5	11,4
2(I	20 U9	16.9	6.30	6.54	5.62	2.91
?5	9.88	5.74	2.94	2.10	3.14	1.33
30	4.83	2 .50	1.98	1.08	2.39	0.787
35	2.45	1.1?	2.51	0.686	2.11	0.559
40	1.53	0.628	? . 5 ?	0.586	2.35	().498
45	1.?2	0.50-/	(2.03)	0.486	(2. 13)	0.494
50	0.890	0.454	1.43	0.458	1.58	0.420
60	0. 605	0.296	0.752	0.400	0.814	0.312
70	0.467	0.174	0.143	0.237	().11 ?-	0.150
80	0.345	0.0798	0.0659	0.0857	0.07?9	0.0578
90	0.259	0.0582	0.480	0.0681	0.276	0.0514
1 0()	0.?55	0.0759	0.389	0.105	0.447	0.0941
110	0.239	0,0645	0.404	0.101	0.326	0.090
120	0.285	0.0412	0.151	().()493	0.140	0.0ss7
130	0.409	0.0387	o.oi21	().0230	0.0309	0.0144
140	(0.42)	(0.062)	(0.0078)	(0.037)	(0.0075)	(0.096)
150	(0.35)	(0.10)	(0.050)	(0.071)	(0.048)	(0.30)
160	(0.26)	(0. 15)	(o. 16)	(0.096)	(0.13)	(0.60)
170	(0.18)	(0.19)	(0.32)	(0.088)	(0.21)	(0.93)
180	(0.15)	(0.22)	(0.53)	(0.018)	(0.28)	(1 .3)
Q_I	(30.71)*	(35.99)*	34.6	(36.98)*	?6.7	(30.97)*
Q^M			4 .08		3.66	

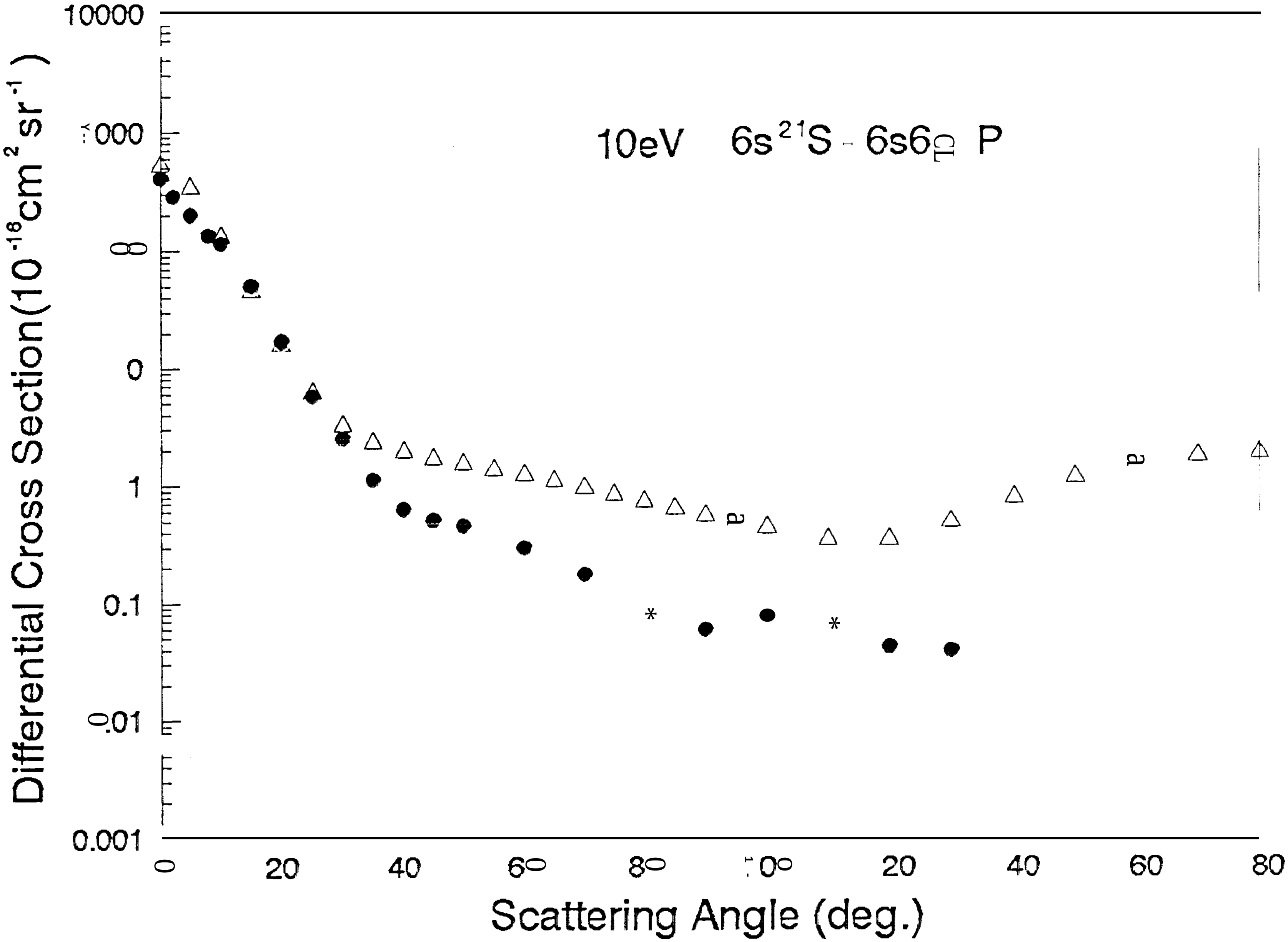
* These are the integral cross sections from optical measurements of Chen and Gallagher (19"/6) after subtraction of the estimated cascade contributions, and are used to normalize the presentl y measured differential cross sections.

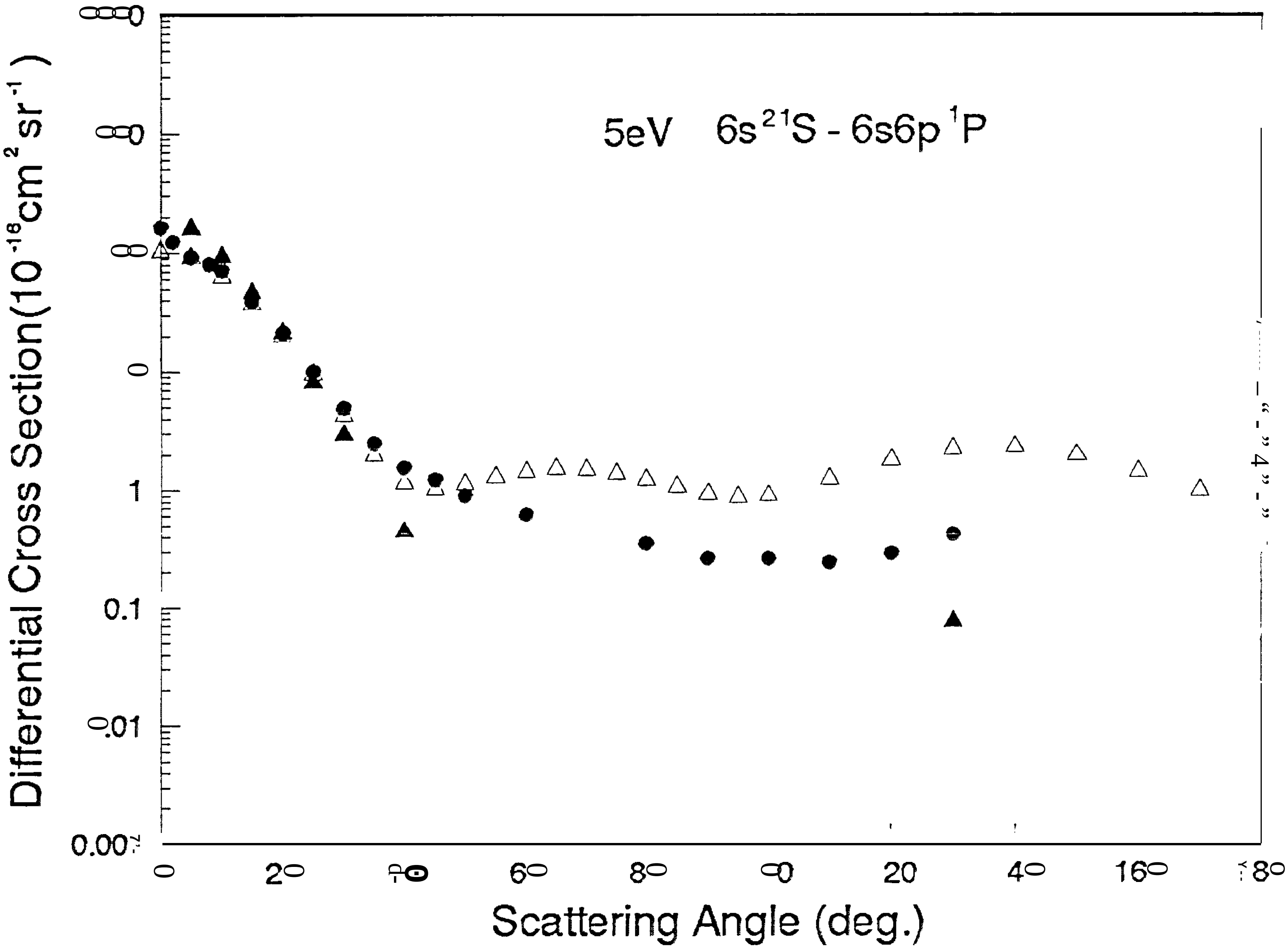
Q_I: the integral cross section.
Q^M: the momentum transfer cross section.


20eV 6s$^{2\,1}$S - 6s6p ^{1}P
Differential Cross Section(10^{-16}cm^{2}sr^{-1})
Scattering Angle (deg.)
0.001
0.01
0.1
1
0
20
40
60
80
100
120
140
160
80

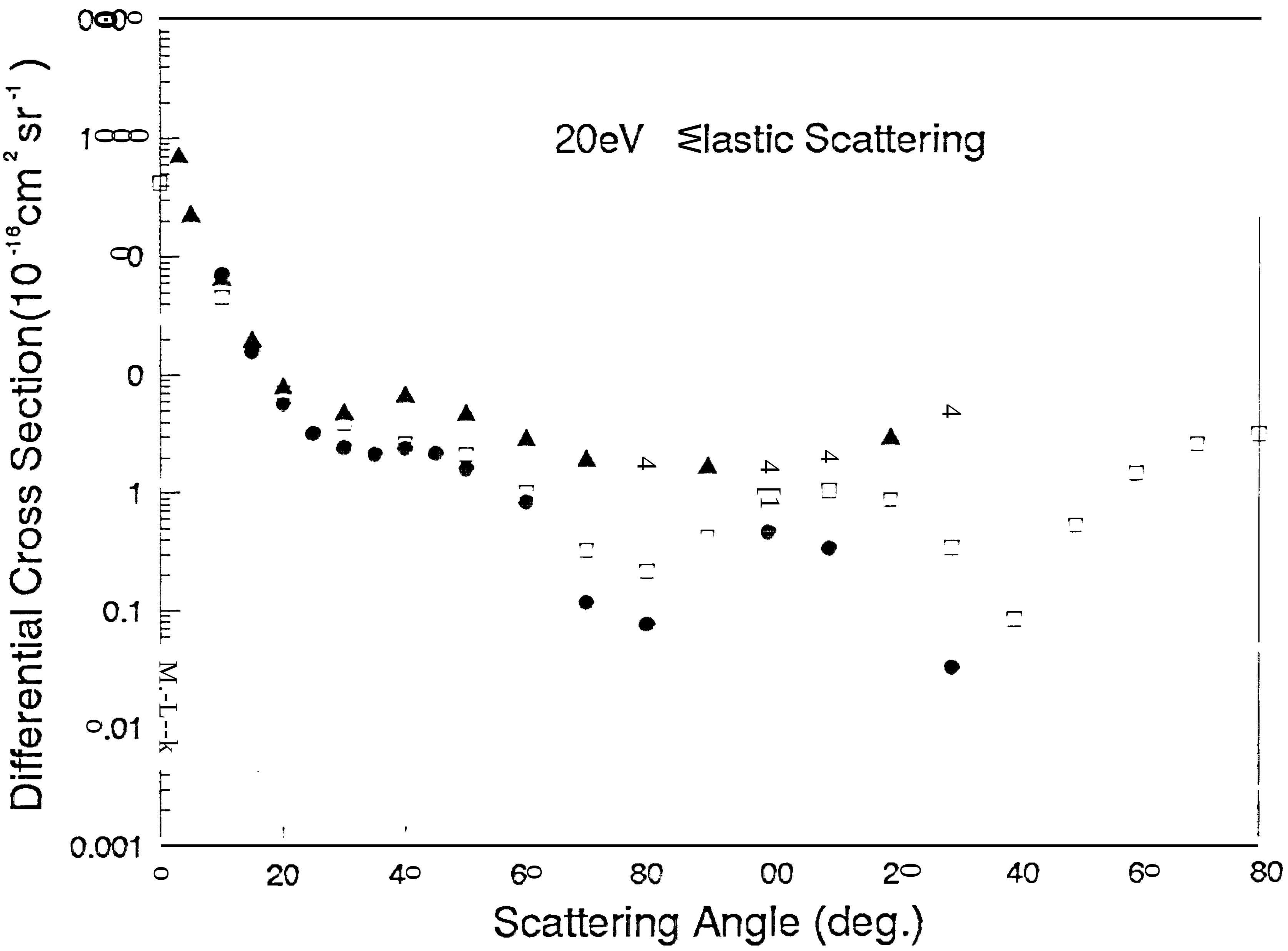


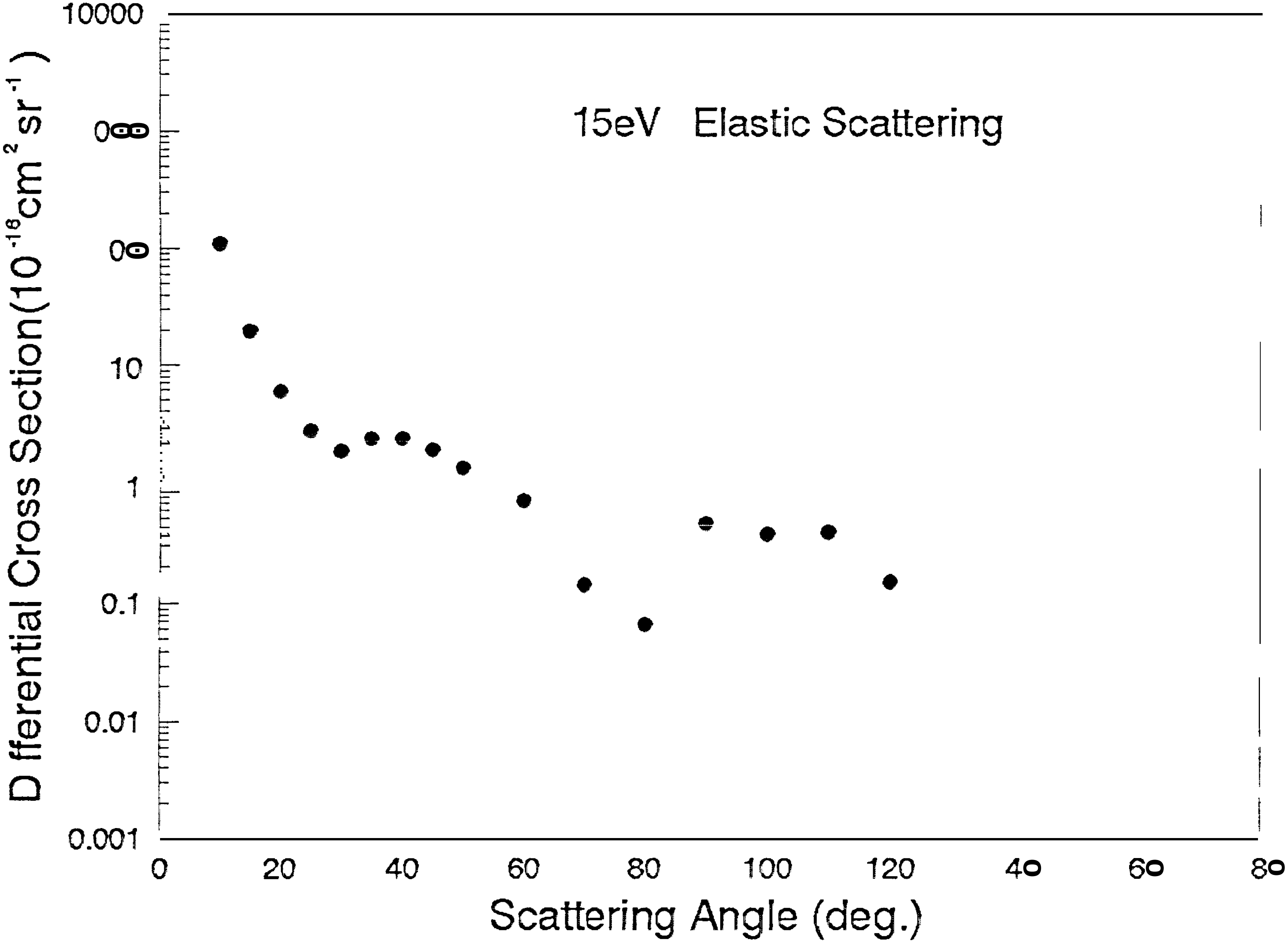
15eV 6s$^{2\,1}$S - 6s6p ^{1}P
Differential Cross Section(10^{-16}cm^2 sr^{-1})
Scattering Angle (deg.)


10eV 6s^{2} ^{1}S - 6s6 P
Differential Cross Section (10^{-18}cm^{2} sr^{-1})
Scattering Angle (deg.)
10000
1
0.1
0.001
0
20
40
20
40
60
80



5eV 6s^{2} ^{1}S - 6s6p ^{1}P
Differential Cross Section(10^{-18}cm^{2}sr^{-1})
Scattering Angle (deg.)
0.1
1
0.01
0
20
60
80
120
140
160


20eV Elastic Scattering
Differential Cross Section ($10^{-16}cm^2 sr^{-1}$)
0.001
0.01
0.1
1
Scattering Angle (deg.)
0
20
80
40
80



15eV Elastic Scattering
Differential Cross Section($10^{-16}cm^2sr^{-1}$)
10000
10
1
0.1
0.01
0.001
0
20
40
60
80
100
120
Scattering Angle (deg.)